Effects of Gap Resistance and Failure Location on Prompt Fission Gas Release from a Cladding Breach

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Abstract

A prompt fission gas release model incorporating the resistance to gas flow in the gap was developed and the effects of gap resistance and failure location on prompt fission gas release from the cladding breach were assessed. The process of prompt fission gas release from the plenum and gap into the coolant was modeled in accordance with three major phenomena: (1) transient gas flow in the gap, (2) the growth of the fission gas bubble while it is still attached to the breach, and (3) the detachment of the fission gas bubble from the breach and mixing with the coolant. The cumulative mass release fraction by the present model was calculated for the case of Young-Gwang 3 & 4 nuclear fuel rod as a typical example. The results showed that the release behavior of prompt fission gas with time was different from the frictionless model which has frequently been used in a simplified approach, and that the location of cladding failure was another key factor for the prompt fission gas release process due to the resistance in the gap.

I. Introduction

A number of investigation has already been made for the release of fission gas from the fuel to the environment, but relatively little attention has been paid to the release of fission gas from the gap of a failed fuel rod into the coolant. In addition, the role of the cladding for the fission gas release has often been neglected in the safety analysis.

If the cladding fails due to the high pressure in the fuel pellet-cladding gap, which is the case considered in the present paper, the fission gas is released from the gap into the coolant via two processes, i.e., the prompt and the delayed release processes. Once the cladding fails due to the high gap pressure, the inventory of the fission gas in the plenum and gap promptly escapes from the fuel rod gap through the cladding breach because of the pressure difference between the plenum/gap and the coolant. When the gap and plenum pressure is nearly close to the coolant pressure, the convective release of the fission gas ceases and the delayed release processes such as diffusion, leaching, and coolant intermixing in the gap and plenum become the dominant release mechanism of the fission gas.

The first process, i.e., prompt release process of the fission gas is focused in the present paper. This process has been studied by several authors[1-4], but most of their works, which are related to liquid-metal fast breeder reactors, were focused on the pressure pulses generated in the coolant due to fuel pin failure and little effort was made to describe the prompt fission gas release. El-Genk et

al.[5] and Fernandez & Thomas[6] tried to analyze this process in terms of the prompt fission gas release. El-Genk et al. developed the prompt fission gas release model but their work was not realistic because they neglected the effects of the resistance to the gas flow in the tortuous gap, which might be the key factor for the fission gas release rate. Because of the absence of friction, the prompt fission gas release ceased very quickly. However, Idaho National Engineering Laboratory (INEL) experimental data show that the plenum pressure continues to decrease after hundreds of seconds[7]. It is very likely that the fission gas is released very slowly, because after irradiation the fuel has swollen and is in close contact with the cladding, providing a lot of resistance to the gas flow in the gap. Fernandez and Thomas developed a simple model incorporating the gap resistance for the fission gas release from failed liquid-metal fast breeder reactor fuel rods. But their model requires an effective permeability which is a parameter a priori unknown.

In addition, the resistance to the gas flow in the tortuous gap gives a relationship for the behavior of the fission gas release depending on the axial location of the cladding breach. If the cladding breach is located close to the plenum, the flow resistance is relatively small and the discharge of the fission gas may be relatively faster. But if the cladding breach is located near the bottom of a fuel rod when there is only one plenum at the top as shown in Fig. 1, the flow resistance will be maximum and the discharge of the fission gas may be very slower.

In the present paper, the resistance to the gas flow in the gap is incorporated in the prompt fission gas release model and the effects of failure location on the prompt fission gas release through the cladding breach will be assessed.

II. Model for Prompt Fission Gas Release

Assumptions and Physical Model

When the cladding is failed, the pressure in the plenum and gap decreases as non-condensable fission gas such as xenon and krypton flows out from the gap into the flowing coolant. Because of the surface tension, fission gas forms a bubble at the cladding breach and the gas bubble grows as the fission gas in the plenum and gap moves into the breach of cladding. In the long run, the fission gas bubble is detached from the breach of cladding due to buoyancy, drag and others. Once the fission gas bubble moves away from the breach of cladding, a new bubble forms and starts to grow. These growth and detachment processes continue until the plenum/gap pressure becomes equal to the coolant pressure. At this moment, the prompt release of fission gas from the plenum and gap is considered to be stopped.

The main assumptions of the present work for the prompt release process are: (1) the fission gas behaves as a perfect gas, (2) the fission gas bubble is a sphere, (3) the gas flow in the tortuous gap is one dimensional and laminar, (4) the gas flow in the tortuous gap is friction-dominated, (5) the gas flow in the tortuous gap is isothermal, and (6) internal structures such as the spring are neglected.

Transient Gas Flow in the Gap

As shown in Fig. 1 the fuel rod is divided axially into an arbitrary number of computational cells. Pressure and density are defined at cell centers, and flow rates are defined at cell interfaces. The mass conservation equation for the fission gas in the gap is written for a computational cell centered at k and Δz_k long:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k A_k \Delta z_k) + (\alpha \rho u_z)_k A_k - (\alpha \rho u_z)_{k-1} A_k = 0 \tag{1}$$

Here α, ρ, A, and u_z are the flow area fraction, the density, the cross-sectional area inside the cladding, and axial gas velocity in the gap. The flow area fraction, α, is represented by the annular gap between the internal cladding and the fuel pellet. For each half-cell, the momentum conservation equations for the fission gas in the gap are

$$(\alpha A)_k \frac{\Delta z_k}{2} \frac{\partial}{\partial t}(\rho u_z)_k + (\alpha A)_k P' - (\alpha A)_k P_k + K_k(\rho u_z)_k(\alpha A)_k \frac{\Delta z_k}{2} = 0 \tag{2}$$

and

$$(\alpha A)_{k+1} \frac{\Delta z_{k+1}}{2} \frac{\partial}{\partial t}(\rho u_z)_{k+1} + (\alpha A)_{k+1} P_{k+1} - (\alpha A)_{k+1} P' + K_{k+1}(\rho u_z)_{k+1}(\alpha A)_{k+1} \frac{\Delta z_{k+1}}{2} = 0 \tag{3}$$

where P is the pressure, P' is the common interface pressure between half-cells, and K is the flow resistance factor.

Two constitutive equations, an equation-of-state and a specification for the flow resistance factor, are required for closure. The equation-of-state for a perfect gas is expressed as

$$\rho = \frac{P}{RT} \tag{4}$$

where T and R are the gas temperature and the gas constant, respectively. The flow resistance factor is specified in an analogous manner to the fluid flow in a tube as follows:

$$K\rho u_z = \frac{f}{D_h} \frac{\rho u_z^2}{2} \tag{5}$$

where f is the Darcy friction factor and D_h is the hydraulic diameter. Assuming that the gas flow is limited to the annulus between the fuel and the cladding, the hydrauic diameter is equal to the diametral gap. The friction factor for laminar flow can be expressed as

$$f = \frac{Ha}{Re} \tag{6}$$

where Re is the Reynolds number and Ha is the Hagen number. For transient fission gas flow in the gap, the following experimental correlation used in TRAP-T6 code[8] has been adopted here:

$$Ha = 22 + \frac{0.24558}{39.3701D_h - 0.0007874} \tag{7}$$

Bubble Growth

In the present work, a simplifying approach adopted by Wu[4] and El-Genk et al.[5] is used, which considers the gas bubble as a growing sphere in contact with a plane surface. As shown in Fig. 1, the momentum balance in the x-direction for the growing fission gas bubble in liquid coolant can be written as follows:

$$\frac{d}{dt}(M_b \dot{r}) = F_M + F_B - F_V \tag{8}$$

where M_b is the bubble mass, r is the bubble radius, F_M is the force due to the rate of change of gas momentum when it exits the breach, F_B is the force exerted on the bubble at the breach due to the pressure difference at the gas/liquid interface, and F_V is the force obstructing the bubble's movement due to the existence of liquid coolant.

Bubble Detachment

At low and intermediate gas flow rates, the fission gas is released in the form of individual bubbles and the detachment diameter of the bubbles in the flowing coolant can be determined from the momentum balance in the direction of the coolant flow. By equating the drag and the buoyancy force to the surface tension, the following expression is obtained :

$$\frac{\pi}{8} C_D \rho_c U_c^2 D^2 + \frac{\pi}{6} D^3 (\rho_c - \rho_b) g = \pi d_f \sigma \tag{9}$$

where C_D, ρ_c, ρ_b, U_c, D, g, d_f are the drag coefficient, the coolant density, the bubble density, the coolant velocity, the detachment diameter, the acceleration of gravity, and the breach diameter, respectively.

At high gas flow rates, the fission gas emerges in a more or less as a continuous jet. In the jet regime, the detachment phenomenon of the bubbles is somewhat more complicated. Using Rayleigh's results, Silberman[9] derived the largest bubble diameter, D_{max}, formed from the jet as follows:

$$D_{max} = 2.4\left(\frac{Q}{U_c}\right)^{1/2} \text{, for } \frac{Q}{U_c} < 4.9 \times 10^{-3} \frac{U_c^{\ 4}}{g^2} \tag{10a}$$

where Q is the volumetric flow rate of gas. When (Q/U_c) becomes very large, the jet rises mainly because of buoyancy. Then Eq. (10a) should be modified as[9]:

$$D_{max} = 1.41\left(\frac{Q^2}{g}\right)^{1/5} \text{, for } \frac{Q}{U_c} \geq 4.9 \times 10^{-3} \frac{U_c^{\ 4}}{g^2} \tag{10b}$$

Silberman performed an experiment to substantiate Eq. (10a). In his experiment, the bubbles vary from the largest, which corresponds roughly to the size of that when they are pinched off by a corrugation of the air jet, to the smaller bubbles, which are remnants of large bubbles with fragments removed, and finally to the fragments themselves. He concluded that the size distribution of the bubbles below the largest should be obtained only from experiment. In the present study, however, the maximum bubble diameter predicted by Eq. (10) is considered as the detachment diameter of the bubble since the largest bubbles correspond to the volume of the gas pinched off from the jet by an unstable disturbance wave.

Since the diameter obtained from Eq. (10) decreases as Q decreases, the detachment diameter determined from Eq. (9) may be used as a lower limit to Eq. (10)[9]. Jet flow will prevail after the diameter obtained from Eq. (10) is greater than the detachment diameter calculated from Eq. (9).

III. Numerical Results and Discussion

Comparison with INEL's Experiment

The ability of the finite difference approach for the transient gas flow in the gap is demonstrated by the comparison with Idaho National Engineering Laboratory (INEL) experimental data of transient gas flow test[7]. The plenum pressure predicted by the present model is compared with test data for Rod K-4 in Fig. 2. While the pressure decay for 60 μm diametral gap (the INEL's recommended value) is relatively faster than the data, the agreement is good for 50 μm diametral gap. Because INEL's recommended value of 60 μm diametral gap has an uncertainty on the order of 30%, the prediction by the present model for transient gas flow in the gap can be considered to be good.

Effects of Gap Resistance and Failure Location

The Young-Gwang 3 & 4 nuclear fuel rod is selected to investigate the effects of the gap resistance and the failure location on the prompt fission gas release. The Young-Gwang 3 & 4 nuclear fuel rod has an upper plenum only. In addition, the following parameters are selected for the example case: (1) initial rod pressure $= 20\,MPa$; (2) coolant pressure $= 15.51\,MPa$; (3) fission gas temperature $= 1200\,K$; (4) coolant velocity $= 6\,m/s$; (5) final breach area of the cladding $= 2.0 \times 10^{-7}\,m^2$; (6) diametral gap $= 60\,\mu m$.

It is assumed that cladding ballooning does not occur during the prompt release process, since the main objective of this work is to investigate the effects of the resistance on the fission gas release. The properties of Xe-136 are used as those of fission gas, since Xe-136 becomes a major component of fission gas within an intact fuel rod as burnup increases.

As shown in Fig. 3, the cumulative mass release fraction by the present model incorporating the friction in the gap is very different from those obtained by the frictionless model which has

frequently been used in simplified approach. In addition, the termination time of the prompt fission gas release is prolonged about several orders of magnitude. It is a very strong function of the final breach area of cladding as well as the initial pressure difference between the plenum/gap and the coolant.

Due to the role of the resistance in the gap on the prompt fission gas release process, the location of cladding failure can be another key factor for the prompt fission gas release process. Figure 4 shows the cumulative mass release fraction versus time for two different locations of the cladding failure. For the Young-Gwang fuel rod, the effect of the resistance in the gap is maximum in the case of failure at the lowest location of the fuel rod, and the effect of the resistance in the gap is minimum in the case of failure at the upper plenum. As can be seen in Fig. 4, the effect of the resistance to gas flow in the gap is small when failure occurs at the upper plenum and therefore, the results are similar to the frictionless case.

IV. Conclusions

A prompt fission gas release model incorporating the resistance to gas flow in the gap was developed and the effects of gap resistance and failure location on the prompt fission gas release from the cladding breach were assessed. The result of calculation for the cumulative mass release fraction by the present model showed that the release behavior of prompt fission gas with time was different from the frictionless model which has frequently been used in a simplified approach, and that the location of cladding failure was another key factor of prompt fission gas release process due to the role of the resistance in the gap on the prompt fission gas release process.

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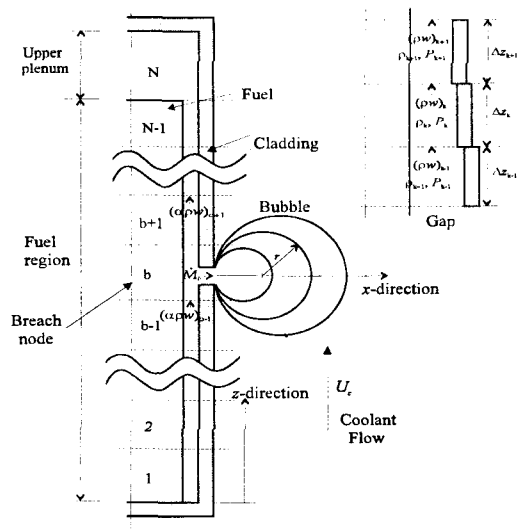
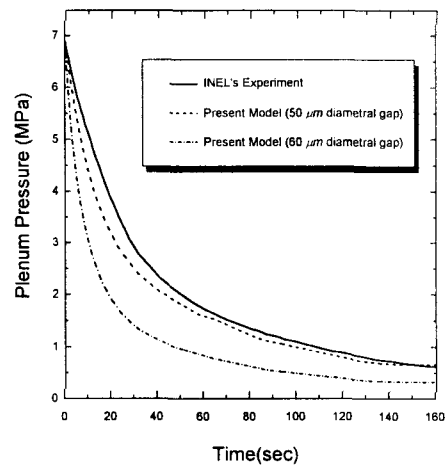Fig. 1 Physical model for the present work.

Fig. 2 Comparison of the present model with INEL's experiment (fuel length = 3.65 m, plenum length = 0.17 m, diametral gap (recommended) = 60 μm, temperature = 25 °C, initial pressure = 6.9 MPa, final pressure = 0.1 MPa, fill gas = helium).
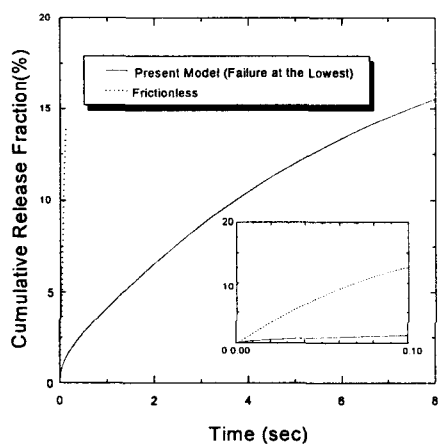
Fig. 3 Comparison of cumulative mass release fraction between the present and the frictionless model.
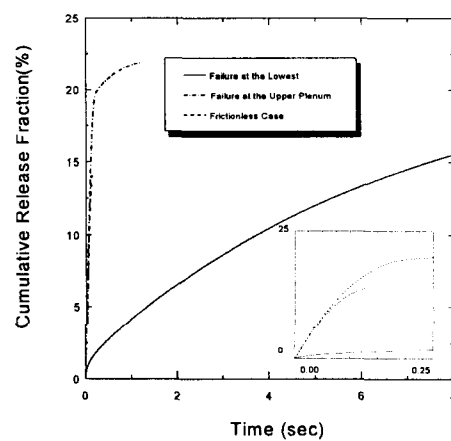
Fig. 4 The effect of failure location on cumulative mass release fraction.